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Abstract

WAM (acronym for WAve Model) is a third-generation wave model used to compute the spectra of random short-crested wind-generated waves on Eulerian grids and is one of the most extensively tested and widely used wave models in the world. Waves can be propagated on a spherical or a Cartesian grid. For large ocean regions, waves must be propagated on a sphere to account for the curvature of the earth. For coastal and nearshore regions, smaller nests with higher mesh resolution are used. As the size of the nests becomes smaller, the differences between a spherical grid and a Cartesian grid for the same nest become smaller and one would assume that the differences in the computed results would also be small. However, this may not be true since the wave transport equation when written in spherical coordinates is not divergence-free whereas it is divergence-free when written in Cartesian coordinates. In nearshore regions, finite-depth effects such as bottom friction, shoaling, and refraction become important and the effect of divergence, when finite-depth effects become important, has not been studied. The purpose of this study was to test the spherical and Cartesian wave propagation schemes in the WAM code to determine their effect on nearshore wave predictions. The test case was a simulation of wind-wave activity during 1995 Hurricane Luis. This study found that Cartesian wave propagation produced more accurate nearshore wave predictions than spherical wave propagation.

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Keywords: WAM, nearshore wave prediction, 1995 Hurricane Luis, spherical wave propagation, Cartesian wave propagation

1 Introduction

One of the major challenges in ocean modeling is the accurate prediction of nearshore wave conditions. Accurate nearshore wave conditions are necessary for environmental impact studies of erosion and sediment transport and play an equally important role in naval navigation and landing operations.

The WAM code has been primarily developed to generate open-ocean wave predictions. In large ocean regions, waves must be propagated using a spherical grid to account for the curvature of the earth's surface. The WAM code can also be applied in coastal and nearshore regions using source terms to model finite-depth effects such as bottom friction, shoaling, and refraction. In these regions the size of the nests is smaller compared to a large ocean nest and the differences between the spherical and Cartesian predictions should become smaller as the size of the nest decreases. However, this may not be true owing to the different nature of the spherical and Cartesian grid systems. Komen et al. [2] noted that the wave-action transport equation in spherical coordinates is not divergence-free. This occurs because the wave direction, measured from true north, changes while the wave group propagates over the globe along a great circle. However, the effect of the wave propagation scheme on nearshore wave predictions does not appear to have been studied.

The purpose of this study was to apply the WAM code in nearshore zones to study the effects of spherical and Cartesian wave propagation on the accuracy of the nearshore wave predictions. The selected test case is a simulation of wind-wave activity during 1995 Hurricane Luis for which NOAA buoy and station data was available, as well as data from the U. S. Army Field Research Facility at Duck, NC. Comparison of the WAM results with the wave observations permits evaluation of the codes and indicates where certain models should or should not be applied. This study shows that, on the Atlantic Ocean continental shelf, the significant wave heights are more accurately predicted with the WAM code when Cartesian wave propagation is used.

2 Description of the WAM code

WAM is a third generation wave model, which computes spectra of random short-crested wind-generated waves. The WAM code can be used for shallow and deep-water calculations and can account for unsteady current and depth fields. The following basic physics are accounted for in the WAM code:

- Wave propagation in time and space
- Wave generation by wind
- Shoaling and refraction due to depth
- Shoaling and refraction due to current
- Whitecapping and bottom friction
- Quadruplet wave-wave interactions

The WAM model, described in Hasslemann et al. [2], solves an wave-action transport equation (shown here for spherical wave propagation on a great circle path):

$$\frac{\partial N}{\partial t} + (cos\phi)^{-1}\frac{\partial}{\partial \phi}(\dot{\phi}\ cos\phi\ N) + \frac{\partial}{\partial \lambda}(\dot{\lambda}N) + \frac{\partial}{\partial \theta}(\dot{\theta}N) + \frac{\partial}{\partial \sigma}(\dot{\sigma}N) = S_{in} + S_{wc} + S_{nl} + S_{bf}, \quad (1)$$

where

$\mathrm{N}(\phi, \lambda, \theta, \sigma, t)$	= the spectral wave action density
σ	= relative frequency
θ	= wave direction
ϕ	= latitude
λ	= longitude
$\dot{\phi}$	= time rate of change of ϕ
$\dot{\lambda}$	= time rate of change of λ
$\dot{\theta}$	= time rate of change of the propagation direction
S_{in}	= wind input
S_{nl}	= non-linear wave-wave interaction
S_{wc}	= dissipation due to whitecapping
S_{bf}	= dissipation due to bottom friction

WAM uses an explicit first-order accurate upwind scheme in geographical space and can propagate waves on a Cartesian grid or a spherical grid. The WAM documentation can be found on the web (http://www.dkrz.de/forschung/reports/wamh-1-eng.html). WAM is one of the most extensively tested and widely used wave models in the world and is well documented. A detailed description of the WAM code is given by Gunther et al. [1] and Komen et al. [5].

3 WAM deployment

The test sites are located in the Atlantic Ocean on the continental shelf along the outer banks of North Carolina and the coast of Virginia. The WAM computations are compared with data from two NOAA C-MAN stations, one NOAA buoy, and two U. S. Army Field Research Facility (FRF) test sites located at Duck, NC. These sites were selected because data was available for the 1995 September test period that coincided with Hurricane Luis. Table 1 gives the latitude and longitude coordinates for the test sites with their approximate mean water depths. The water depths for NOAA buoy 44014 and the FRF 8-m array were taken from the NOAA and FRF web sites. The water depths for NOAA stations chlv2 and dnsl2 were provided by Knoll [4]. The water depth for the FRF buoy wr630 was supplied by Long [6]. NOAA buoy 44014 and test station dsln7 are situated on the edge of the continental shelf (beyond the shelf, the water depth increases rapidly to 3000-4000 m). NOAA buoy wr630 is located 4 km offshore and the FRF 8-m array is 900 m offshore.

Table 1 Test site data

Instrument ID	latitude	longitude	360 + longitude	water depth
NOAA buoy 44014	36.5831 N	-74.8336 W	285.1664	47.5 m
NOAA station dsln7	35.1533 N	-75.2967 W	284.7033	19.0 m
NOAA station chlv2	36.9050 N	-75.7133 W	284.2867	11.6 m
FRF buoy wr630	36.1681 N	-75.6999 W	284.3001	17.1 m
FRF 8-m array	36.1906 N	-75.7421 W	284.2579	8.0 m

Four WAM nests were used in the present study. The nests are referred to as the “basin” (30-minute resolution, 135x120 cells), “region” (15-minute resolution, 120x96 cells), “sub-region 1 (sub1)” (5-minute resolution, 84x120 cells), and “sub-region 2 (sub2)” (5/4-minute resolution; 96x96 cells), moving from coarser to finer resolution. Table 2 gives information concerning the WAM nests. The mesh sizes in km given in Table 2 are only approximate. Table 3 shows additional pertinent information regarding the WAM runs.

In the WAM code, the mesh is generated internally using the maximum and minimum values of the longitude and latitude and the step size values. The data is given in Table 2. For wave propagation in Cartesian space “stereographic projection” which places the wind vector and water depth at the (i,j) location on the spherical mesh at the (i,j) location on the Cartesian mesh. In addition, the cos(lat) in the spherical coordinates is set to 1.

The WAM calculations were made using 25 frequencies and 24 directions with the frequencies

Table 2 WAM nest data

Nest Level	long. (deg.)	lat. (deg.)	resolution (min.)	long. mesh size	lat. mesh size
basin	345/277.5	70/10	30	54.7 km	55.5 km
region	308/278	48/24	15	25.4 km	27.8 km
sub1	290/283	41/31	5	7.9 km	9.3 km
sub2	286/284	35/37	5/4	1.9 km	2.3 km

Table 3 WAM run data

Description	basin	region	sub1	sub2
Propagation time step	12 min	6 min	2 min	1 min
Source term time step	12 min	6 min	2 min	1 min

logarithmically spaced from 1/30 Hz to 1.1 Hz. The water depths are assumed to be the mean values. Currents and tidal effects were not considered in this study.

4 Test case: Hurricane Luis

The path of the eye of Hurricane Luis is indicated by the curving white line in Figure 1, which shows the WAM significant wave height contours for the region nest on 95/09/10, 0 UTC; this date approximately corresponds to the peak of the storm as measured at NOAA buoy 44014. The different WAM nests used can also be seen in Figure 1. At the top right of Figure 1, the date and hour of the wave contours are shown; the state of Florida can be recognized in the lower left corner of the region nest. The coordinates used to plot the hurricane eye path shown in Figure 1 were obtained from the NOAA web site (http://www.nhc.noaa.gov/1995luis.html) and were not taken from the wind fields used to drive the wave simulations.

Figure 2 shows the significant wave height contours for the sub2 nest at 95/09/10, 0 UTC which is the nest used to evaluate the effect of the spherical and Cartesian propagation schemes. Also shown are the five test locations and an additional nest which was not used in this study. Overlaying the NOAA data on contour plots of the wind speed computed from the hindcast wind fields (see below) served to validate that the eye of the hurricane deduced from wind speed and significant wave height contour plots was consistent with the NOAA web site data.

Table 4 summarizes the types of measurements available at the different sites iusing the indicated notations for significant wave height (Hmo), peak wave period (Tmax), and mean wave direction (θ_{mean}).

Table 4 Availability of data

Instrument ID	location	Hmo	θ_{mean}	Tmax
NOAA buoy 44014	Virginia Beach, VA	yes	yes	yes
NOAA station chlv2	Chesapeake Light, VA	yes	no	yes
NOAA station dsln7	Diamond Shls. Light, NC	yes	no	yes
FRF buoy wr630	Duck, NC	yes	no	yes
FRF 8-m array	Duck, NC	yes	yes	yes

The hindcast wind fields used to drive the WAM computations and the bathymetry data for the basin and region nests were provided by Jensen[3]. The wind fields are defined on the basin nest and are interpolated to the region and sub region nests using bi-linear surface interpolation. The bathymetry for sub regions sub1 and sub2 were downloaded from the Naval Oceanographic Office (NAVO) variable resolution gridded bathymetry database (DBDBV) [7].

5 Evaluation methods

During the basin computation, predicted wave spectra are interpolated to the boundaries of the region and saved. Likewise, during the computations for the region nest, spectra are interpolated to the boundaries of the sub1 nest and saved. Similarly, the sub1 nest supplies the boundary conditions for the sub2 nest. The boundary condition spectra, the winds, and the bathymetry drive the computations for the different nests.

The computational results from the WAM runs were examined based on the difference between the calculated values and the instrument measurements using root-mean-square (rms) norms. Biases in the computations relative to the instrument measurements are also examined. These are computed using the ratios ΔH defined as:

$$\Delta H = H_c - H_d \tag{2}$$

where H takes on the values of significant wave height, peak wave period, and mean wave direction and the subscripts "c" and "d" denote "computed" and "data" values. The root-mean-square norm (rms) and the bias are defined as:

$$rms(H) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Delta H_i)^2}, \tag{3}$$

$$bias(H) = \frac{1}{N}\sum_{i=1}^{N}\Delta H_i, \tag{4}$$

where "N" is the number of evaluation points.

The simulation period for this study was 95/08/29, 0 UTC to 95/09/13, 0 UTC. The evaluation period was taken as the 10-day period from 95/09/03, 0 UTC to 95/09/13, 0 UTC; the model spin-up portion of the simulation was not, therefore, used for evaluation purposes.

6 Discussion of results

The effect of the wave propagation method on the significant wave height is given in Table 5. Table 5 shows that the rms values for the Cartesian propagation hindcasts are more accurate than the spherical hindcasts at all five test sites. The bias values exhibit similar behavior at four of the five test sites. Table 6 gives the average significant wave height over the test period for the spherical and

Cartesian results as well as the data. In general, the Cartesian values are closer to the data values. Shown in Table 7 are the errors in the average significant wave height values. Table 7 shows that the accuracy using spherical wave propagation becomes increasingly worse as the waves approach land - see Figure 2. The reason why the Cartesian wave propagation results are more accurate than the

Table 5 Comparison of rms and bias values

	rms, significant wave height, m		
test site	spherical	Cartesian	accuracy bias
NOAA 44014	0.655	0.653	Cartesian
NOAA dsln7	0.595	0.568	Cartesian
NOAA chlv2	0.453	0.349	Cartesian
FRF wr630	0.489	0.417	Cartesian
FRF 8-m array	0.596	0.486	Cartesian
	bias, significant wave height, m		
buoy	spherical	Cartesian	accuracy bias
NOAA 44014	-0.084	-0.095	Spherical
NOAA dsln7	0.076	0.057	Cartesian
NOAA chlv2	0.187	0.089	Cartesian
FRF wr630	0.161	0.072	Cartesian
FRF 8-m array	0.243	0.122	Cartesian

spherical wave propagation results is not clear. It may be related to the fact that the wave-action transport equation is divergence-free in Cartesian coordinates, but not in spherical coordinates. The small differences between the spherical and the Cartesian results at the NOAA buoy 44014 and NOAA station dsln7 test sites are the result of their being on the edge of the shelf where the waves arrive from deep-water where bottom friction, shoaling, and refraction are negligible. Thus, even

Table 6 Average significat wave height, m

site	spherical	Cartesian	data
NOAA 44014	1.94	1.93	2.21
NOAA dsln7	2.13	2.11	2.05
NOAA chlv2	1.38	1.28	1.19
FRF wr630	1.51	1.42	1.35
FRF 8-m array	1.49	1.37	1.24

Table 7 Average error in Hmo for the wave propagation schemes

site	spherical	Cartesian	difference
NOAA 44014	-4.1%	-4.7%	-0.6 %
NOAA dsln7	3.7%	2.8%	-1.0 %
NOAA chlv2	15.7%	7.5%	-8.2 %
FRF wr630	11.9%	5.3%	-6.6 %
FRF 8-m array	19.6%	9.8%	-9.7 %

though one might expect that the spherical propagation would be as accurate or more accurate as the Cartesian hindcasts (due to the more accurate representation of the earth's curvature), this was not found to be true for the sub2 nest. Figures 3-7 show comparisons for the significant wave height results for the two propagation methods for the different test sites. These figures confirm there is very little difference at NOAA buoy 44014 and NOAA dsln7 station, and the largest differences are at the FRF 8-m array.

7 Conclusions

The effect of the wave propagation method used in the WAM model on nearshore wave prediction has been examined. The test case was a simulation of 1995 Hurricane Luis for which test data was available. The nest used to evaluate the propagation schemes was a two degree by two degree zone located in the Atlantic Ocean along the outer banks of North Carolina and the coast of Virginia comprising five test sites. This study found Cartesian wave propagation to be more accurate than spherical wave propagation for nearshore wave predictions.

8 Acknowledgement

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Figure 1 Region: WAM significant wave height: 95/09/10, 0 UTC

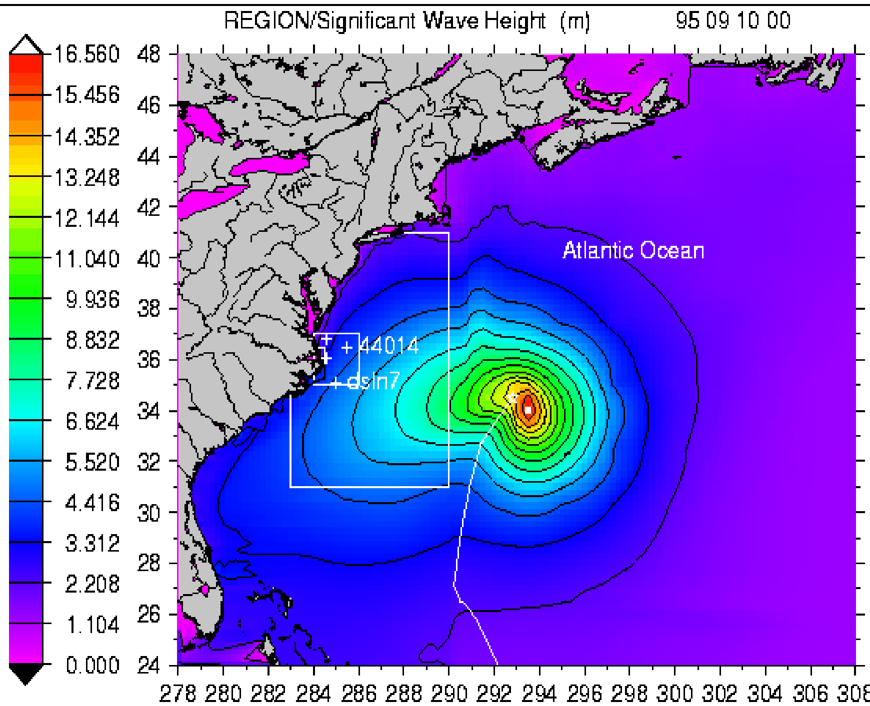

Figure 2 sub2: WAM significant wave height: 95/09/10, 0 UTC

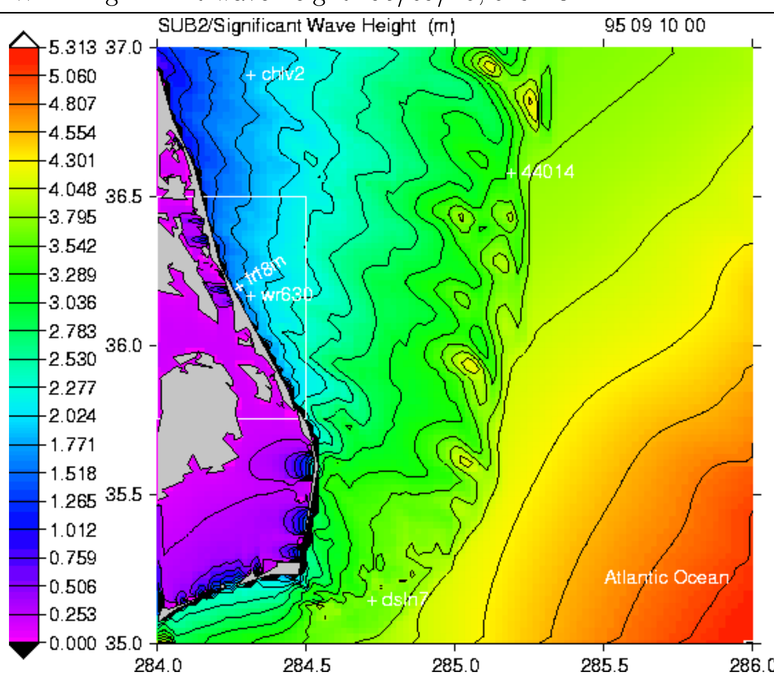

Figure 3 The effect of wave propagation method on Hmo: NOAA buoy 44014

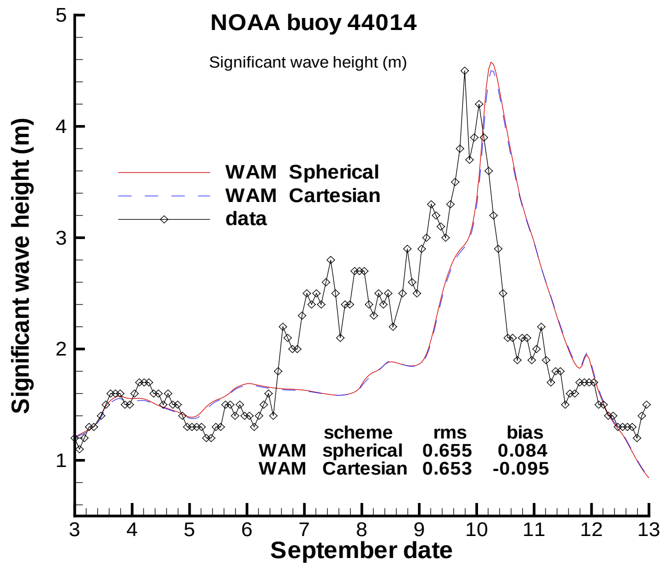

Figure 4 The effect of wave propagation method on Hmo: NOAA station dsln7

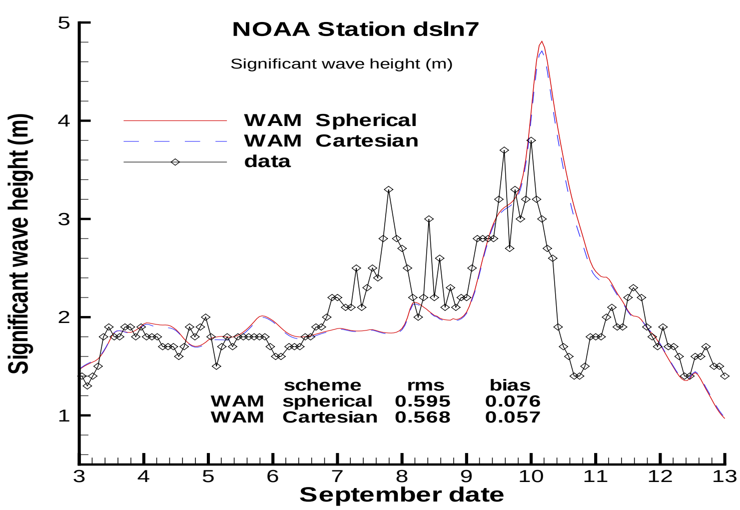

Figure 5 The effect of wave propagation method on Hmo: NOAA station CHLV2

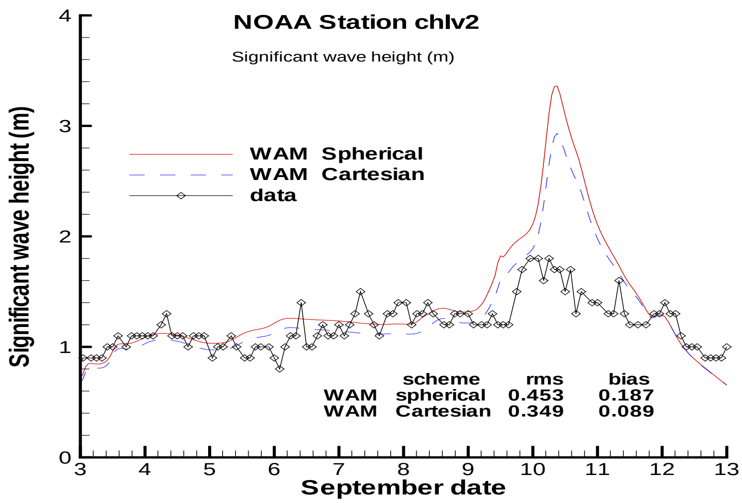

Figure 6 WAM: the effect of spherical and Cartesian wave propagation on Hmo: FRF 8-m array

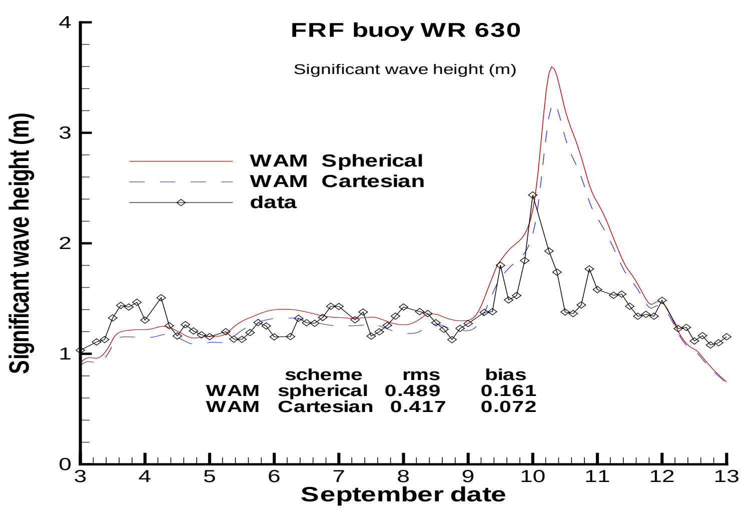

Figure 7 WAM: the effect of spherical and Cartesian wave propagation on Hmo: FRF 8-m array